# DISCIPLINED RUBIDIUM OSCILLATOR WITH GPS SELECTIVE AVAILABILITY

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**Abstract**

***A U.S. Department of Defense decision for continuous implementation of GPS Selective Availability (S/A) has made it necessary to modify Rubidium oscillator disciplining methods. One such method for reducing the effects of S/A on the oscillator disciplining process has been developed which achieves results approaching pre-S/A GPS.***

***This paper describes the Satellite Hopping algorithm used in minimizing the effects of S/A on the oscillator disciplining process, and compares the results of using this process to those obtained prior to the implementation of S/A. Test results are from a TrueTime Rubidium based Model GPS-DC timing receiver.***

## INTRODUCTION

Our goal in the disciplining process is to maintain a frequency accuracy of better than $10^{-11}$ at all times and to do this with a minimal effect on oscillator stability. In disciplining the Rubidium oscillator, the philosophy is one of limited intervention. During normal operation, the Rubidium oscillator is sampled and adjusted once per day. This technique takes full advantage the Rubidium oscillator's short term stability, correcting only for frequency errors accumulated during the one day period.

Prior to the implementation of S/A, each daily frequency sample was 16 minutes 40 seconds in duration. The results were good as the Rubidium oscillator remained well within the $10^{-11}$ design limit, with an average frequency error of $3 \times 10^{-12}$ and an Allan Deviation of $2.5 \times 10^{-12}$ at a $\tau$ of 1 day[1]. When S/A was was implemented, however, the disciplining algorithm included the S/A term in the Rubidium control solution and misadjusted the oscillator. In an attempt to correct the apparent Rubidium oscillator frequency error, the disciplining algorithm reduced the control period, allowing multiple samples per day which only exacerbated the errors. Rubidium oscillator performance was degraded by almost an order of magnitude.

S/A was also degrading the time transfer accuracy of the GPS-DC (GPS-Digital Clock) in which the disciplined Rubidium oscillator is installed. A method was needed that would reduce the effects of S/A on the disciplining process and the time transfer process as well.

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## SELECTIVE AVAILABILITY

At current levels, satellites with S/A enabled show typical time transfer errors of ±200 nanoseconds, occasionally peaking to ±350 nanoseconds.

Figures 1 and 2 show typical time transfer stability of two satellites, one with S/A applied and one without. Both satellites are referenced to the Rubidium Oscillator. The satellite with S/A shows peak to peak timing variations of more than 400 nanoseconds over the 2 hour period, while the satellite without S/A applied has normally less than 70 nsec.

Figure 3 compares the Allan Deviation of both satellites (the SatHop plot is discussed later). The difference in time transfer stability over 10 to 50,000 seconds in this graph shows a four times degradation in stability at current S/A levels.

## SATELLITE HOPPING

A Satellite Hopping (SatHop) Algorithm has been developed to reduce the effects of S/A on time transfer and frequency disciplining processes. Satellite hopping takes advantage of the fact that a timing receiver requires only one satellite for accurate time transfer. However, any one satellite can transfer a timing error of 300 nanoseconds or more for a random period of time. If several satellites are sampled sequencially and averaged into a composite satellite solution, the effects of the satellites with S/A should be reduced. Additionally, the satellites without S/A will tend to further reduce the errors caused by the satellites with S/A.

Figure 4 is a typical plot of the output directly from the GPS receiver during the Satllite hopping process. Timing solutions from satellites with S/A enabled can be seen mixed with those satellites without S/A. Note that the frequency of the S/A component in this composite satellite has been increased by the hopping period, making it easier to average.

The SatHop Algorithm has two components, a satellite seqeuncer and a solution averager. The sequencer scans the list of satellites currently being tracked and selects one satellite for the GPS receiver to use for timing solutions (user deselected and unhealthy satellites are skipped). As the GPS receiver can track up to seven satellites simultaneously, all visible satellites are normally on the list. After a dwell period of 30 seconds which generates 30 samples for the selected satellite, the next satellite in the sequence is selected. The sequencer continuously loops through the satellite list, which is updated by the GPS receiver as satellites rise and set.

The solution averager creates a composite satellite Clock Bias solution by averaging the phase solutions from all of the tracked satellites into a single 400 sample average. Clock Bias, in units of meters, represents the phase comparison between the Rubidium Oscillator and GPS and is described under System Hardware.

The output of the SatHop solution averager can be seen in Figure 5. This output is an averaged composite phase measurement between all tracked satellites and the Rubidium oscillator. The graph shows how quickly the effects of Selective Availability can be reduced. Averaging a single satellite with Selective Availability enabled will not produce these results. The Allan deviation of the SatHop solution averager can be seen in Figure 3. When tracking three or more satellites this plot tends towards the non-S/A satellite plot.

## SYSTEM HARDWARE

Referring to Photograph 1, the unit under test is a GPS Digital Clock with the Disciplined Rubidium option installed. Referring to Photograph 1, the GPS satellite receiver and Rubidium oscillator are both contained within the Clock, along with other clock electronics.

The oscillator being disciplined is an FRS–C Rubidum oscillator manufactured by Ball Corporation, Efratom Division. It is an integral component of the GPS–DC and is the clock's timebase (located in center of clock).

The GPS receiver is a TTM (Tans Timing Module), manufactured by Trimble Navigation(located in front center of clock). The receiver uses the Disciplined Rubidium oscillator as its' timebase when performing position and timing solutions. Thus, when the GPS receiver performs time transfer solutions, variations in the solution can be attributed to the Rubidium oscillator, Selective Availability, variations in GPS signal path, and system noise.

The variable the TTM uses to report the phase difference is Clock Bias, and has units of meters. Clock Bias os directly converted to seconds using the speed of light in free space ($3.335640952 \times 10^{-09}$ seconds/meter) as the conversion factor. Clock Bias has a usable resolution of a few nanoseconds.

## THE DISCIPLINING PROCESS

The disciplining algorithm is a variable period frequency locked loop which controls the Rubidium for zero frequency error. The disciplining algorithm adjusts the Rubidium once each control period. At the end of a control period, a 4000 sample average of Clock Bias is taken (ten sample averages from the SatHop solution averager). Used in conjunction with a previous control period sample, a frequency error is calculated and an adjustment is made to the Rubidium C–field control voltage using a 16–bit D/A converter.

The disciplining algorithm also contains a control period calculator. This calculator is designed to determine the shortest possible control period allowable for an accurate frequency measurement at the current Rubidium oscillator frequency error. The control period is calculated using a simple hyperbolic curve:

$$\text{(Control Loop Period)} = \text{K}/\text{(Rubidium Frequency Error)}$$

where K is a constant calculated to ensure S/A does not impact the required measurement accuracy. The control loop period is limited to minimum and maximum period values. The minimum control period limit is calculated to satisfy the allowable worst case oscillator accuracy, and is currently set at 6000 seconds. The maximum period value is set at 86400 seconds. This one day period is desirable as it allows for cancellation of most daily variances, including those due to daily temperature variations. Once an oscillator has reached the maximum control loop period it tends to remain there unless the oscillator is disturbed.

A hardware temperature compensation circuit reduces the temperature sensitivity of the Rubidium. This circuit measures the temperature of the Rubidium oscillator baseplate and sums a temperature

correction voltage into the Rubidium oscillator C–field adjust input as a feed–forward term. The gain of the temperature compensation circuit is characterized for each Rubidium oscillator. The circuit removes a substantial portion of the temperature sensitivity of the Rubidium oscillator. The temperature sensitivity of the Rubidium oscillator in this test was reduced to better than $2.0 \times 10^{-12}$ per degree Centigrade.

## TEST RESULTS AND CONCLUSIONS

Data taken during the months of August and October 1992 consists of:

- Clock Bias directly from the GPS receiver as it sequenced through the visible satellites,
- Phase measured between the Rubidium 1 PPS and a Cesium 1PPS
- Cesium 1PPS compared to the GPS-DC 1PPS.

The Rubidium remained within $+5.5 \times 10^{-12}$ and $-6.8 \times 10^{-12}$ with variances due to temperature, the Disciplining algorithm, and the Rubidium oscillator frequency stability.

Figure 6 is an Allan Deviation plot of the Rubidium 1 PPS compared to the Cesium 1PPS. The plot shows a degredation in stability at 100,000 seconds which is caused by daily disciplining algorithm adjustments and by daily temperature variations.

The peak frequency error of the Rubidium oscillator during the testing period, assuming all errors belong to the Rubidium, was $-6.8 \times 10^{-12}$ during a 6 degree Centigrade ambient transient. Test performed using the frequency locked loop prior to the advent of Selective Availability (June of 1989 ) resulted in a value of $2.2 \times 10^{-12}$.[1] Note that the temperature did not vary by more than 2 degrees C during the June 1989 test. Also included are results of a test performed in August of 1992. the August and October tests used the same equipment but in different locations. The June 1989 test was performed prior to S/A and is included here for comparison.

Disciplined Rubidium Oscillator Frequency Accuracy

| TEST DATE | S/A ENABLED | PEAK FREQ ERROR | FREQUENCY STABILITY @ 1 DAY | PEAK TEMPERATURE VARIATION, DEGREES C |
|---|---|---|---|---|
| OCTOBER 1992 | YES | $-6.8 \times 10^{-12}$ | $2.51 \times 10^{-12}$ | 7 |
| AUGUST 1992 | YES | $5.6 \times 10^{-12}$ | —— | 5 |
| JUNE 1989 | NO | $3.0 \times 10^{-12}$ | $2.5 \times 10^{-12}$ | 2 |

The stability of the disciplined Rubidium oscillator in an S/A environment are approaching the pre–S/A results. The temperature variations in the tests are once again the predominant variable in the disciplining process.

Improving Rubidium oscillator temperature compensation and/or controlling the temperature of the oscillator baseplate is necessarily the next step in the disciplining process. Improving temper-

ature performance will reduce the peak frequency errors and improve the frequency stability over the 1/2 to 2 day region.

It is interesting to note that the Rubidium Oscillator used in the GPS–DC exhibits a thermal hysteresis on the order of $1\times10^{-12}$ to $3\times10^{-12}$ such that the frequency at a specific temperature will be different depending upon which direction in temperature the final temperature was approached.

The June, 1989 test was performed at a facility with an environmentally controlled labortory.

The August, 1992 test was performed in the TrueTime Engineering offices where the office temperature is controlled by a wall thermostat which was set for the range of 69–71 degrees F.

The October, 1992 test was performed inside an environmental chamber in order to minimize temperature effects on the test. The chamber failed during the test, allowing variations in temperature larger than either previous test. The worst of the failed temperature controller data occurred during the final week of the test and was subsequently truncated.

The GPS Digital Clock 1 PPS output corrects for the accumulated time error of the Rubidium Oscillator and does not pass it on to the user.

## References


[1.] Dewey, W.P., *"A GPS Disciplined Rubidium Clock"*, Proc. of the 21st Annual Precise Time and Time Interval (PTTI) Application and Planning Meeting. Washington D.C., (November 1989), 149-160.

SELECTIVE AVAILABILITY TIME ERROR PLOT
SATELLITE WITH S/A

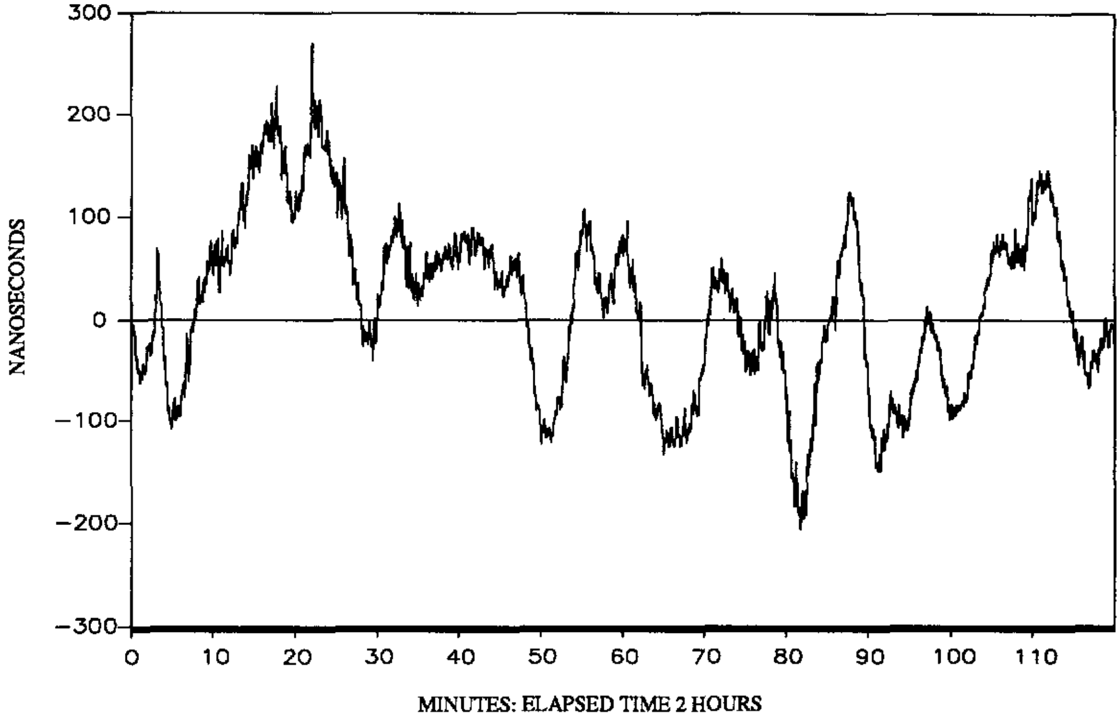



FIGURE 1

SELECTIVE AVAILABILITY TIME ERROR PLOT
SATELLITE WITHOUT S/A

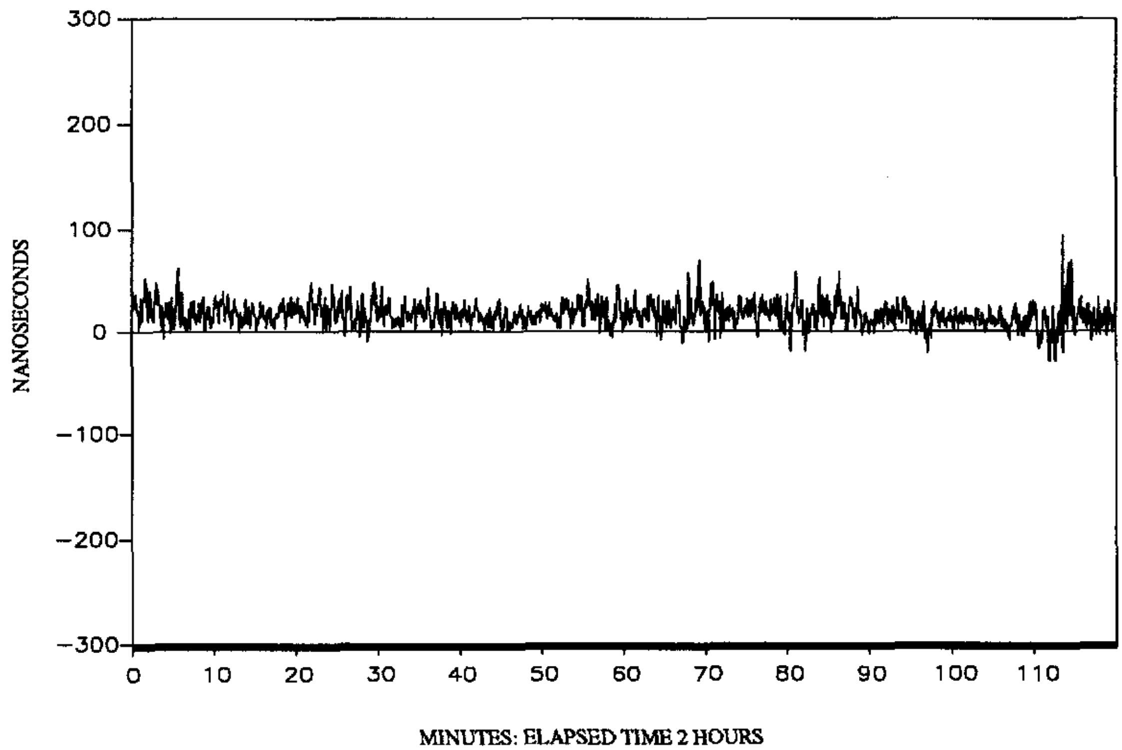



FIGURE 2

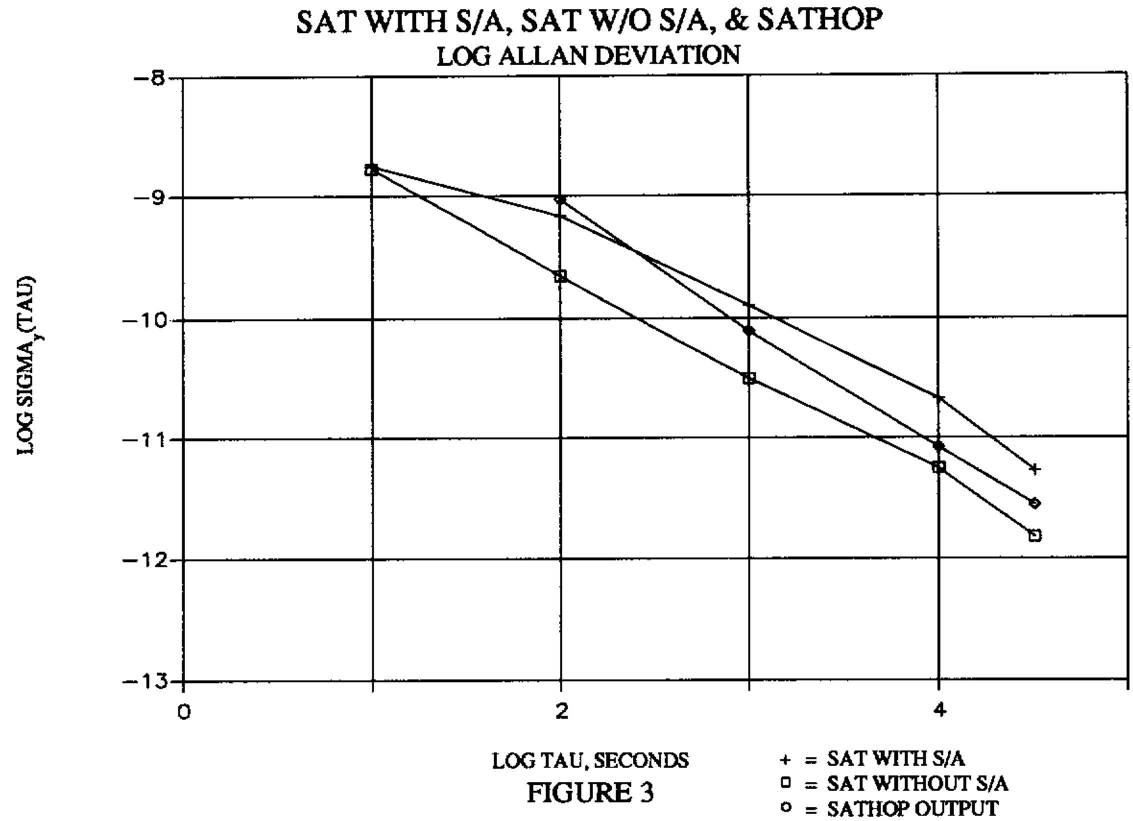



FIGURE 3

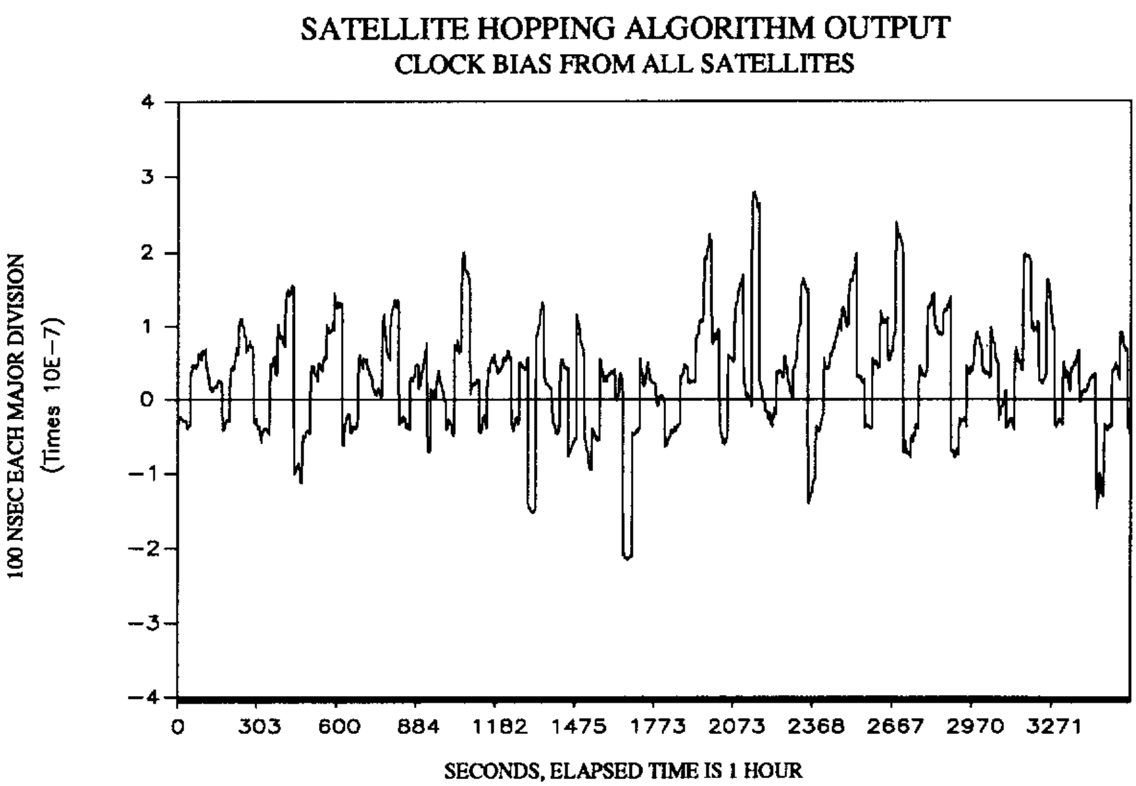



FIGURE 4

SATELLITE HOPPING ALGORITHM OUTPUT
400 POINT AVERAGED CLOCK BIAS

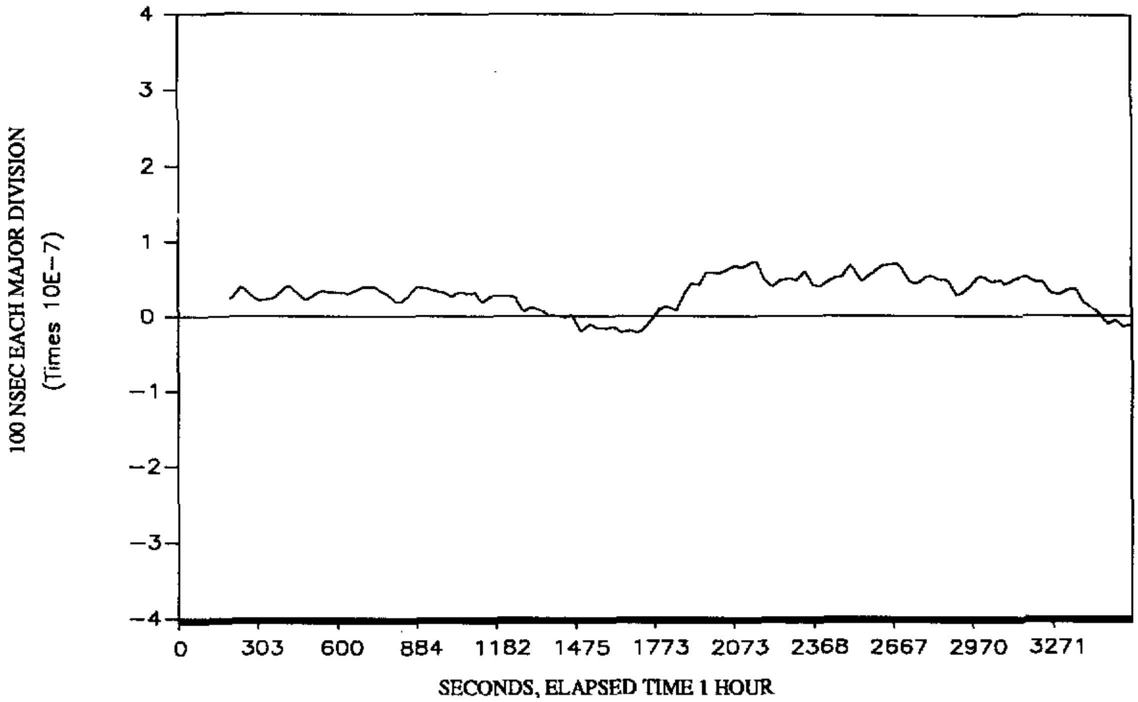



FIGURE 5

RUBIDIUM FREQUENCY STABILITY
ALLAN DEVIATION COMPARED TO CESIUM

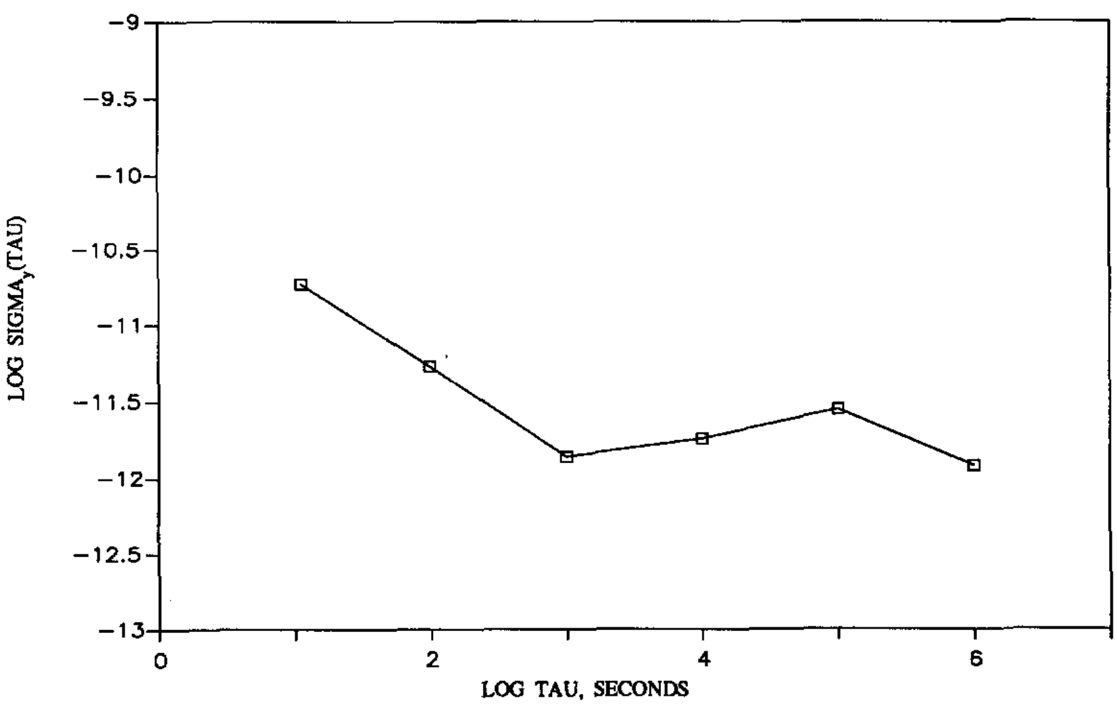
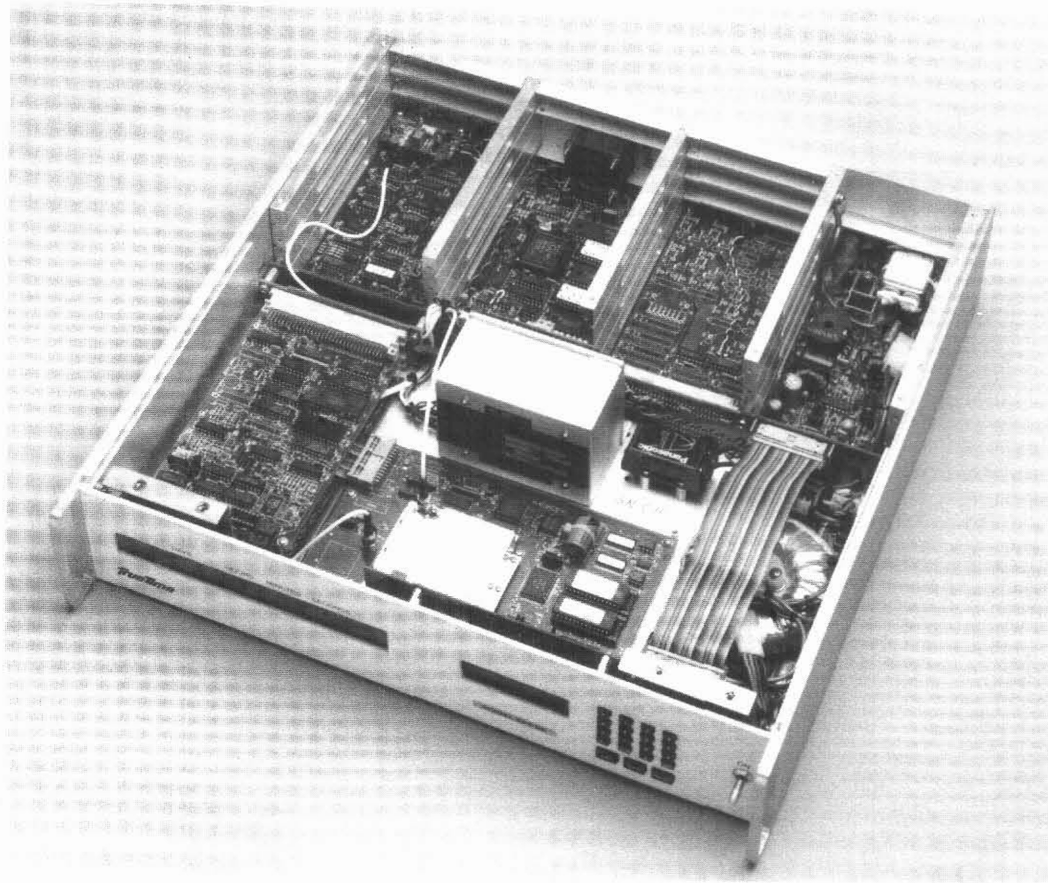



FIGURE 6



GPS DIGITAL CLOCK